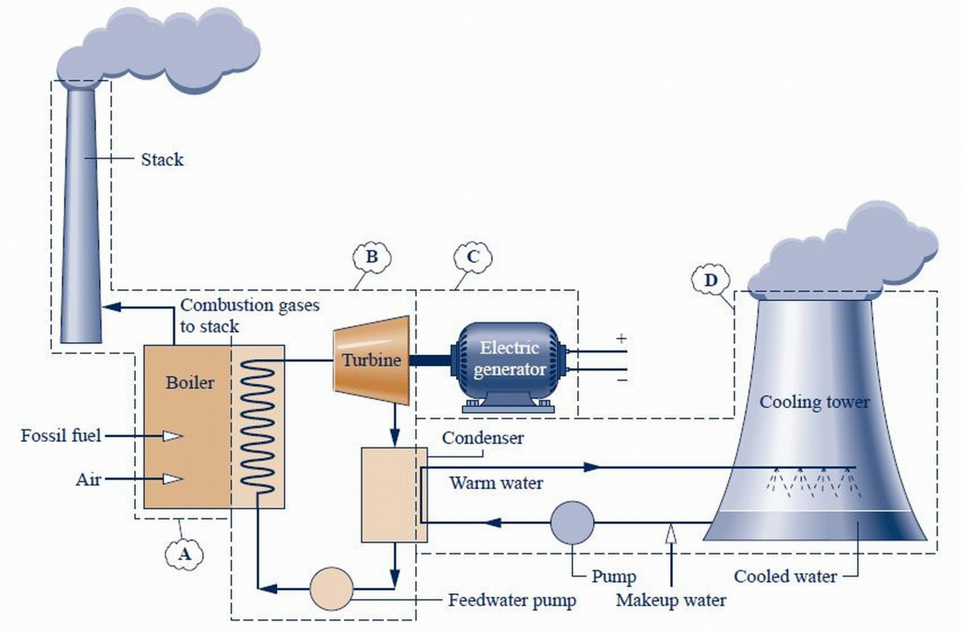
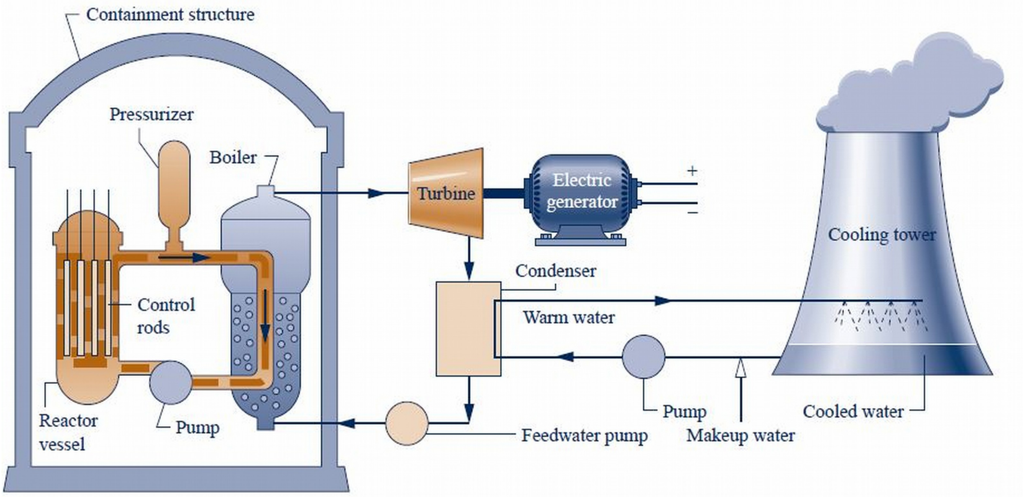
VAPOR POWER SYSTEMS

DIFFERENT TYPES OF POWER PLANTS



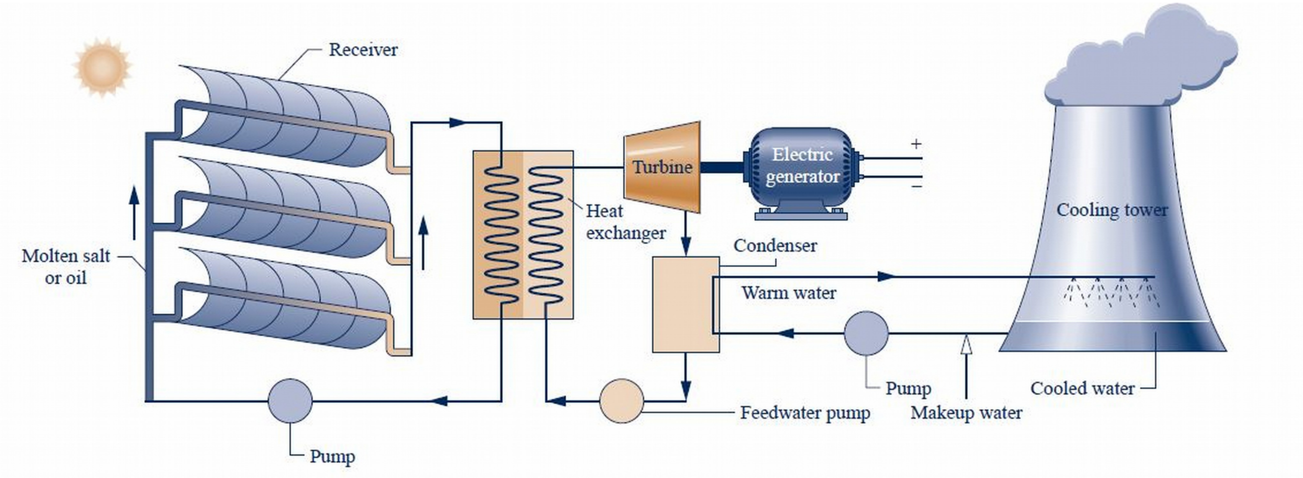
(*a*) Fossil-fueled vapor power plant.

- *In fossil-fueled plants vaporization is accomplished by heat transfer to water passing through the boiler tubes from hot gases produced in the combustion of the fuel. This is also seen in plants fueled by biomass, municipal waste (trash), and mixtures of coal and biomass.*



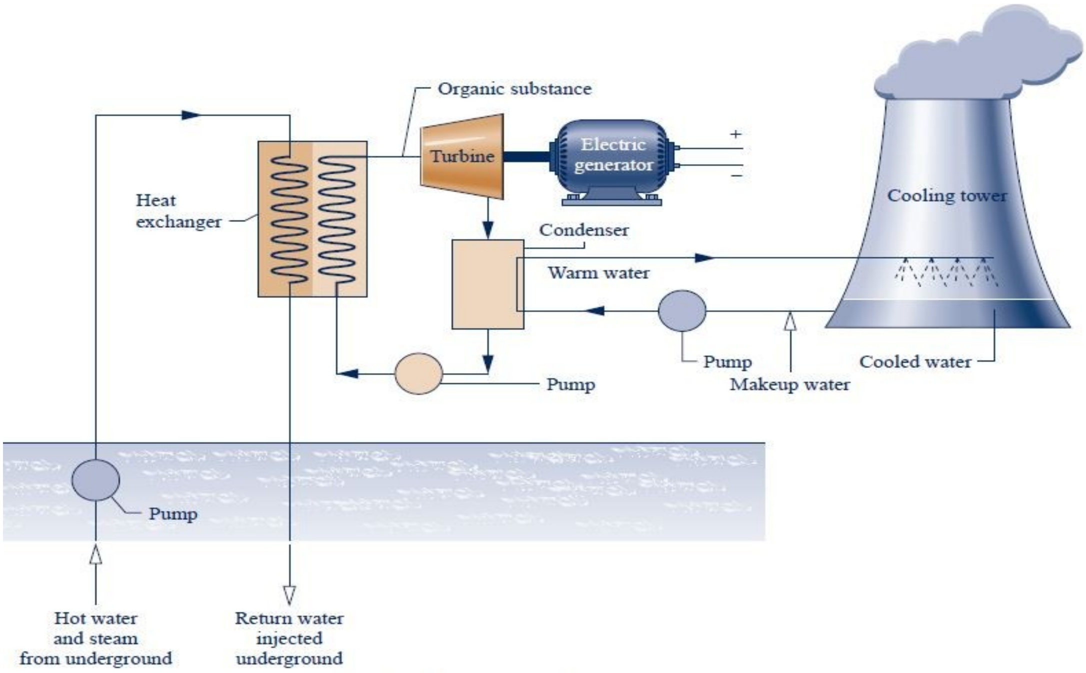
(*b*) Pressurized-water reactor nuclear vapor power plant.

- *In nuclear plants, energy required for vaporizing the cycle working fluid originates in a controlled nuclear reaction occurring in a reactor-containment structure. The pressurized-water reactor has two water loops: One loop circulates water through the reactor core and a boiler within the* *containment structure; this water is kept under pressure so it heats but does not boil. A separate loop carries steam from the boiler to the turbine. Boiling-water reactors have a single loop that boils water flowing through the core and carries steam directly to the turbine.*



(*c*) Concentrating solar thermal vapor power plant.

- *Solar power plants have receivers for collecting and concentrating solar radiation. A suitable substance, molten salt or oil, flows through the receiver, where it is heated, directed to an interconnecting heat exchanger that replaces the boiler of the fossil- and nuclear-fueled plants, and finally returned to the receiver. The heated molten salt or oil provides energy required to vaporize water flowing in the other stream of the heat exchanger. This steam is provided to the turbine.*



(*d*) Geothermal vapor power plant.

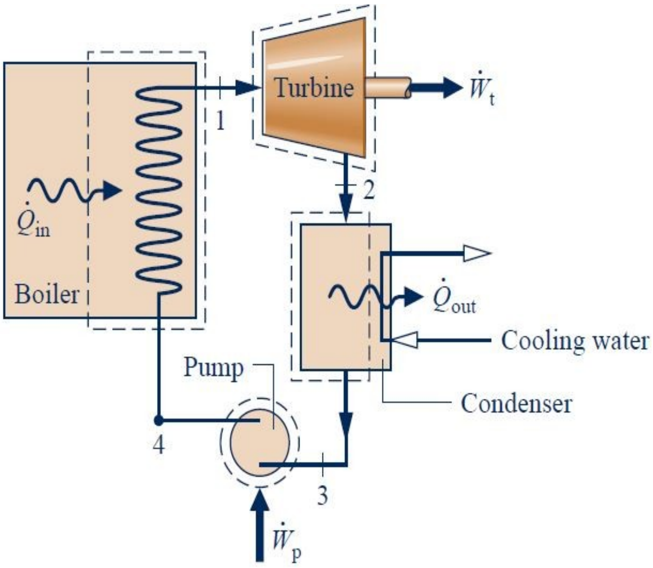
- *The geothermal power plant also uses an interconnecting heat exchanger. In this case hot water and steam from deep below earth's surface flows on one side of the heat exchanger. A secondary working fluid having a lower boiling point than the water, such as isobutane or another organic substance, vaporizes on the other side of the heat exchanger. The secondary working fluid vapor is provided to the turbine.*

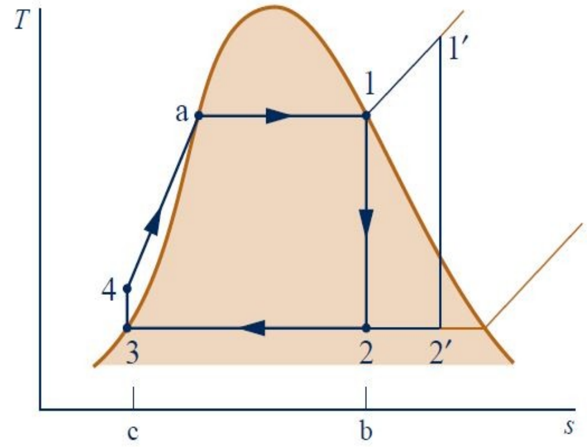
THE RANKINE CYCLE

The four principal components are: turbine, condenser, pump, and boiler.

ASSUMPTIONS

- *The unavoidable heat transfer that takes place between the plant components and their surroundings is neglected for simplicity.*
- *Kinetic and potential energy changes are also ignored.*
- *Each component is regarded as operating at steady state.*
- *Working fluid passes through the various components of the simple vapor power cycle without irreversibilities.*
- *Frictional pressure drops would be absent from the boiler and condenser, and the working fluid would flow through these components at constant pressure.*





PROCESSES AND T-S DIAGRAM

Process 1–2: *Isentropic expansion of the working fluid through the turbine from saturated vapor at state 1 to the condenser pressure.*

Process 2–3: *Heat transfer from the working fluid as it flows at constant pressure through the condenser with saturated liquid at state 3.*

Process 3–4: *Isentropic compression in the pump to state 4 in the compressed liquid region.*

Process 4–1: *Heat transfer to the working fluid as it flows at constant pressure through the boiler to complete the cycle.*

HEAT AND WORK INTERACTIONS

TURBINE : *Vapor from the boiler at state 1, having an elevated temperature and pressure, expands through the turbine to produce work and then is discharged to the condenser at state 2 with relatively low pressure. Work is developed per unit of mass of vapor passing through the turbine-*

$$0 = \cancelto{0}{\dot{Q}_{\mathrm{cv}}} - \dot{W}_{\mathrm{t}} + \dot{m}\left[h_1 - h_2 + \cancelto{0}{\frac{V_1^2 - V_2^2}{2}} + g\cancelto{0}{(z_1 - z_2)}\right]$$

$$\frac{\dot{W}_{\mathrm{t}}}{\dot{m}} = h_1 - h_2$$

CONDENSER: *In the condenser there is heat transfer from the working fluid to cooling water flowing in a separate stream. The working fluid condenses and the temperature of the cooling water increases. The rate at which energy is transferred by heat from the working fluid to the cooling water per unit mass of working fluid passing through the condenser-*

$$\frac{\dot{Q}_{\mathrm{out}}}{\dot{m}} = h_2 - h_3$$

PUMP: *The liquid condensate leaving the condenser at 3 is pumped from the condenser into the higher pressure boiler. The rate of power input per unit of mass passing through the pump-*

$$\frac{\dot{W}_p}{\dot{m}} = h_4 - h_3$$

Because the pump is idealized as operating without irreversibilities and specific volume of the liquid normally varies only slightly; pump work can also be evaluated as-

$$\left(\frac{\dot{W}_p}{\dot{m}}\right)_{\substack{\text{int}\\\text{rev}}} = \int_3^4 v\,dp$$

$$\left(\frac{\dot{W}_p}{\dot{m}}\right)_s \approx v_3(p_4 - p_3)$$

BOILER: *The working fluid completes a cycle as the liquid leaving the pump at 4, called the boiler feedwater is heated to saturation and evaporated in the boiler. The rate of heat transfer from the energy source into the working fluid per unit mass passing through the boiler-*

$$\frac{\dot{Q}_{in}}{\dot{m}} = h_1 - h_2$$

PERFORMANCE PARAMETERS

THERMAL EFFICIENCY: *The thermal efficiency gauges the extent to which the energy input to the working fluid passing through the boiler is converted to the net work output.*

$$\eta = \frac{\dot{W}_t/\dot{m} - \dot{W}_p/\dot{m}}{\dot{Q}_{in}/\dot{m}} = \frac{(h_1 - h_2) - (h_4 - h_3)}{h_1 - h_4}$$

The net work output equals the net heat output. Thus, the thermal efficiency can be expressed alternatively as-

$$\eta = \frac{\dot{Q}_{in}/\dot{m} - \dot{Q}_{out}/\dot{m}}{\dot{Q}_{in}/\dot{m}} = 1 - \frac{\dot{Q}_{out}/\dot{m}}{\dot{Q}_{in}/\dot{m}}$$
$$= 1 - \frac{(h_2 - h_3)}{(h_1 - h_4)}$$

"Thermal efficiency of power cycles tends to increase as the average temperature at which energy is added by heat transfer increases and/or the average temperature at which energy is rejected by heat transfer decreases."

HEAT RATE: *The amount of energy added by heat transfer to the cycle (usually in Btu) to produce a unit of net work output (usually in kWh). Heat rate is inversely proportional to the thermal efficiency.*

BACK WORK RATIO: *It is defined as the ratio of the pump work input to the work developed by the turbine.*

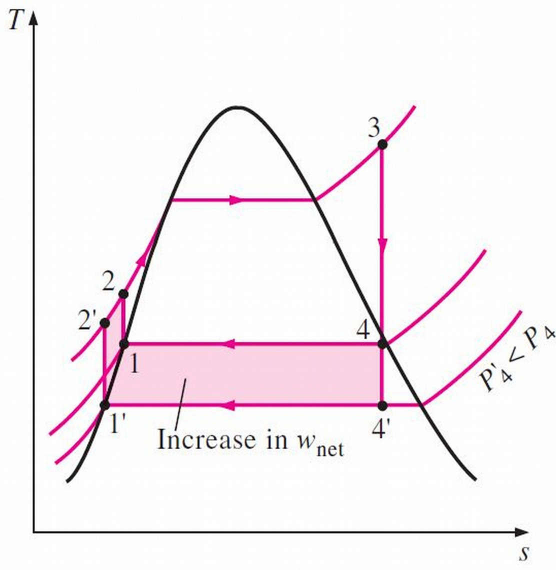
$$\text{bwr} = \frac{\dot{W}_p/\dot{m}}{\dot{W}_t/\dot{m}} = \frac{(h_4 - h_3)}{(h_1 - h_2)}$$

Change in specific enthalpy for the expansion of vapor through the turbine is normally many times greater than the increase in enthalpy for the liquid passing through the pump. Hence, the back work ratio is quite low for vapor power plants.

INCREASING PERFOMANCE

The basic idea behind all the modifications to increase the thermal efficiency of a power cycle is the same: Increase the average temperature at which heat is transferred to the working fluid in the boiler, or decrease the average temperature at which heat is rejected from the working fluid in the condenser.

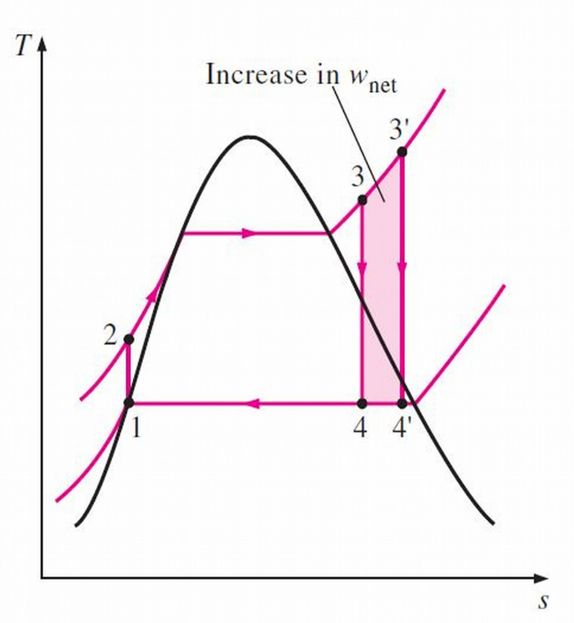
Lowering the Condenser Pressure : (*Lowers* $T_{\text{low,avg}}$)



Steam exists as a saturated mixture in the condenser at the saturation temperature corresponding to the pressure inside the condenser. Therefore, lowering the operating pressure of the condenser automatically lowers the temperature of the steam, and thus the temperature at which heat is rejected. The colored area on this diagram represents the increase in net work output as a result of lowering the condenser pressure. The heat input requirements also increase but this increase is very small. Thus the overall effect of lowering the condenser pressure is an increase in the thermal efficiency of the cycle. To take advantage of the increased efficiencies at low pressures, the condensers of steam power plants usually operate well below the atmospheric pressure. However, there is a lower limit on the condenser pressure that can be used. It cannot be lower than the saturation pressure corresponding to the temperature of the cooling medium. It

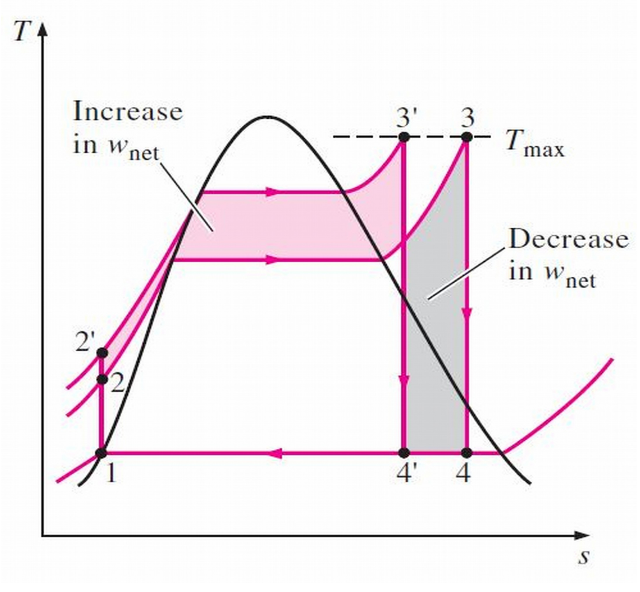
creates the possibility of air leakage into the condenser, increases the moisture content of the steam at the final stages of the turbine.
The presence of large quantities of moisture is highly undesirable in turbines because it decreases the turbine efficiency and erodes the turbine blades.

Superheating the Steam to High Temperatures (*Increases* $T_{\text{high,avg}}$)



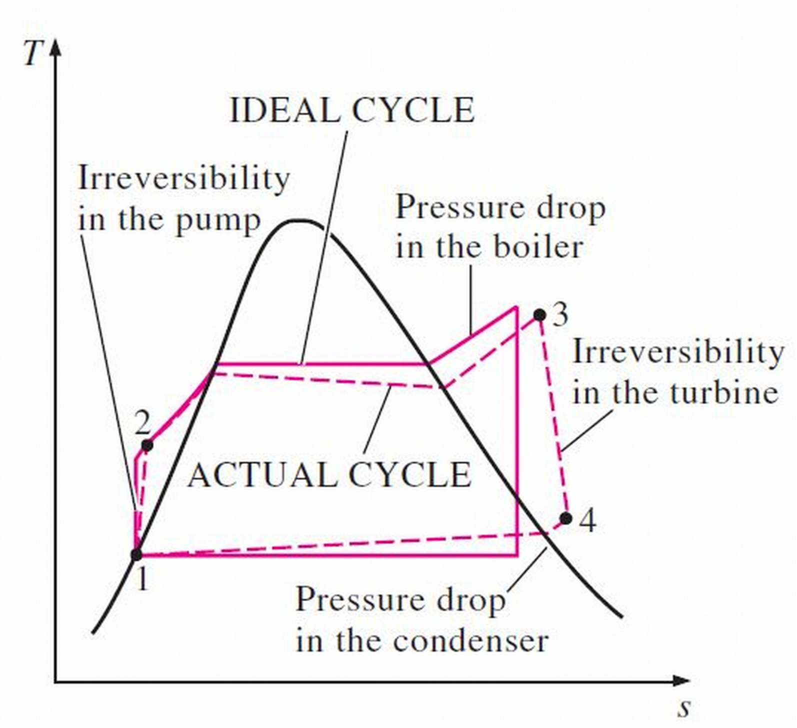
The average temperature at which heat is transferred to steam can be increased by superheating the steam to high temperatures. Both the net work and heat input increase as a result of superheating the steam to a higher temperature. The overall effect is an increase in thermal efficiency, since the average temperature at which heat is added increases. Superheating the steam to higher temperatures has another very desirable effect. It decreases the moisture content of the steam at the turbine exit. The temperature to which steam can be superheated is limited, by metallurgical considerations. Presently the highest steam temperature allowed at the turbine inlet is about 620°C.

Increasing the Boiler Pressure (*Increases* $T_{\text{high,avg}}$)

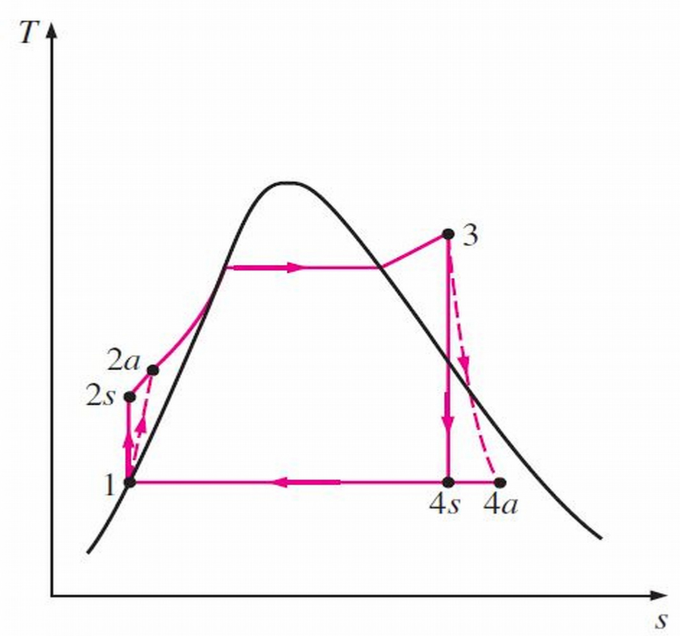


Another way of increasing the average temperature during the heat-addition process is to increase the operating pressure of the boiler, which automatically raises the temperature at which boiling takes place. This, in turn, raises the average temperature at which heat is transferred to the steam and thus raises the thermal efficiency of the cycle. For a fixed turbine inlet temperature, the cycle shifts to the left and the moisture content of steam at the turbine exit increases. This undesirable side effect can be corrected, however, by reheating the steam. Today many modern steam power plants operate at supercritical pressures (P > 22.06 MPa) and have thermal efficiencies of about 40 percent for fossil-fuel plants and 34 percent for nuclear plants.

IRREVERSIBILITIES AND LOSSES


T
IDEAL CYCLE
Irreversibility in the pump
Pressure drop in the boiler
3
Irreversibility in the turbine
2
ACTUAL CYCLE
4
1
Pressure drop in the condenser
s

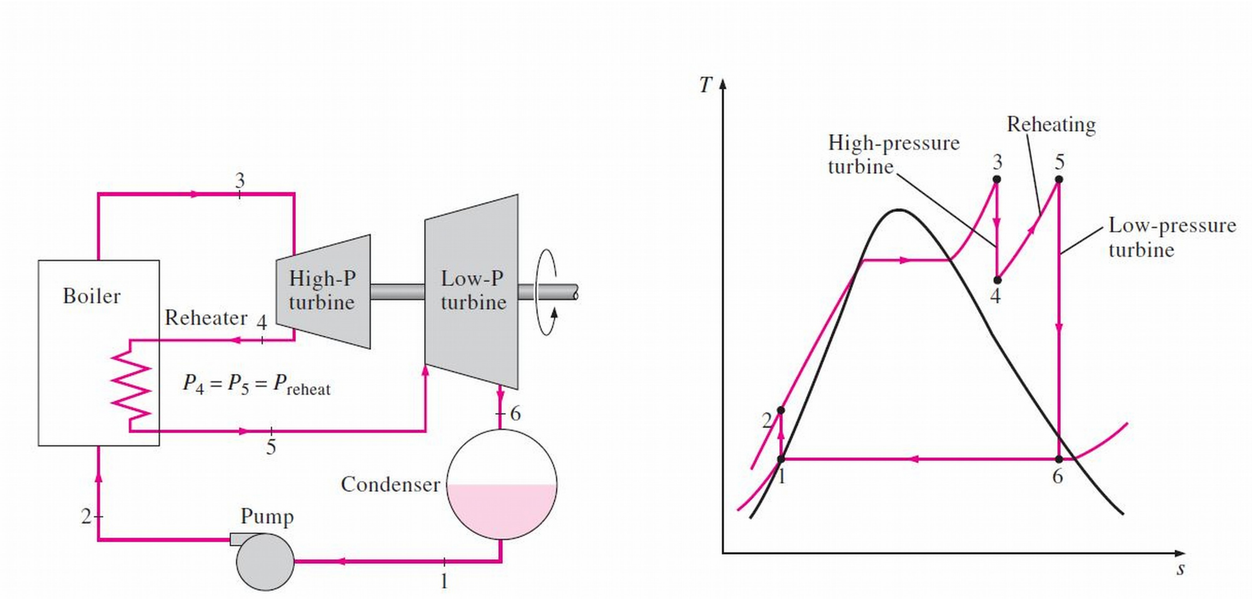
Turbine And Pump Irreversibilities



$$\eta_P = \frac{w_s}{w_a} = \frac{h_{2s} - h_1}{h_{2a} - h_1}$$

$$\eta_T = \frac{w_a}{w_s} = \frac{h_3 - h_{4a}}{h_3 - h_{4s}}$$

REHEAT RANKINE CYCLE:



By the help of reheat Rankine cycle we can take advantage of the increased efficiencies at higher boiler pressures without facing the problem of excessive moisture at the final stages of the turbine.

- *In ideal reheat Rankine cycle expansion process takes place in two stages. In the first stage (the high pressure turbine), steam is expanded isentropically to an intermediate pressure and sent back to the boiler where it is reheated at constant pressure, usually to the inlet temperature of the first turbine stage. Steam then expands isentropically in the second stage (low-pressure turbine) to the condenser pressure.*
- *The reheat temperatures are very close or equal to the turbine inlet temperature. The optimum reheat pressure is about one-fourth of the maximum cycle pressure. The incorporation of the single reheat in a modern power plant improves the cycle efficiency by 4 to 5 percent by increasing the average temperature at which heat is transferred to the steam.*
- *The sole purpose of the reheat cycle is to reduce the moisture content of the steam at the final stages of the expansion process. If we had materials that could withstand sufficiently high temperatures, there would be no need for the reheat cycle.*
- *As the number of stages is increased, the expansion and reheat processes approach an isothermal process at the maximum temperature. The use of more than two reheat stages, however, is not practical. The theoretical improvement in efficiency from the second reheat is about half of that which results from a single reheat. If the turbine inlet pressure is not high enough, double reheat would result in superheated exhaust. Double reheat is used only on supercritical-pressure (P >22.06 MPa) power plants.*

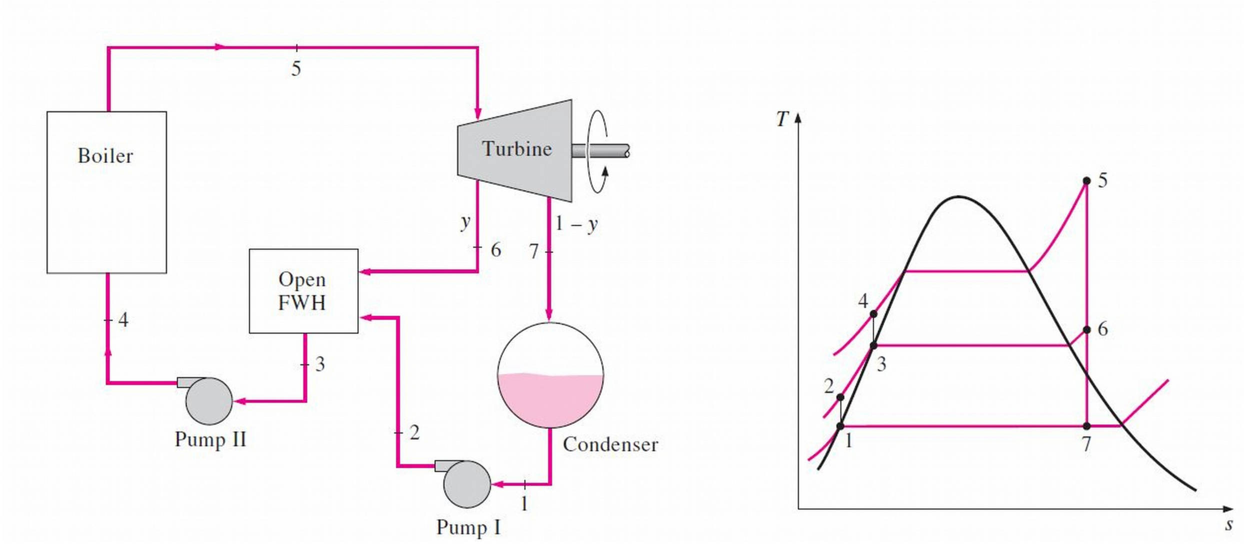
The total heat input and the total turbine work output for a reheat cycle is-

$$q_{\text{in}} = q_{\text{primary}} + q_{\text{reheat}} = (h_3 - h_2) + (h_5 - h_4)$$

$$w_{\text{turb,out}} = w_{\text{turb,I}} + w_{\text{turb,II}} = (h_3 - h_4) + (h_5 - h_6)$$

REGENERATIVE RANKINE CYCLE

REGENERATIVE CYCLE WITH OPEN FWH



- *Regeneration raises the temperature of the liquid leaving the pump (called the feedwater) before it enters the boiler. This increases the average heat addition temperature and thus the cycle efficiency.*

- *Regeneration not only improves cycle efficiency, but also provides a convenient means of deaerating the feedwater (removing the air that leaks in at the condenser) to prevent corrosion in the boiler and controls the large volume flow rate of the steam at the final stages of the turbine.*

- *A practical regeneration process in steam power plants is accomplished by extracting, or "bleeding," steam from the turbine at various points. This steam, which could have produced more work by expanding further in the turbine, is used to heat the feedwater instead. The device where the feedwater is heated by regeneration is called a* ***regenerator,*** *or a* ***feedwater heater (FWH).***

- *Heat and work interactions are-*

$$q_{\text{in}} = h_5 - h_4$$

$$q_{\text{out}} = (1 - y)(h_7 - h_1)$$

$$w_{\text{turb,out}} = (h_5 - h_6) + (1 - y)(h_6 - h_7)$$

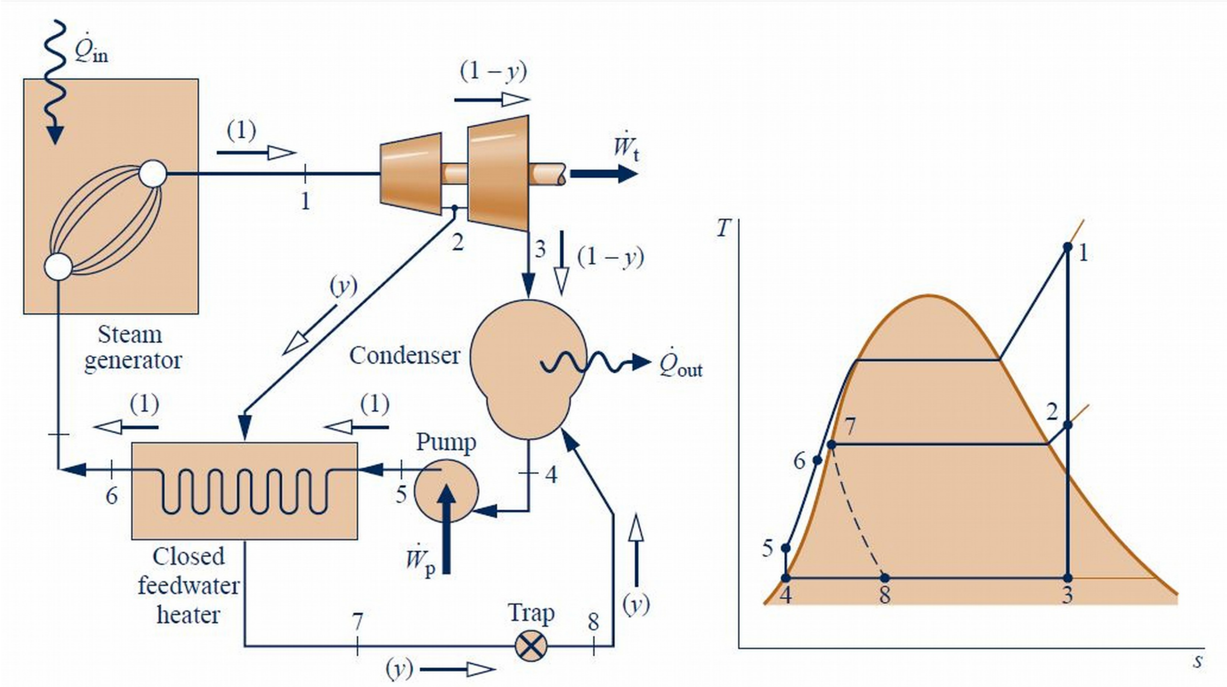
$$w_{\text{pump,in}} = (1 - y)w_{\text{pump I,in}} + w_{\text{pump II,in}}$$

$$y = \dot{m}_6/\dot{m}_5 \qquad \text{(fraction of steam extracted)}$$

$$w_{\text{pump I,in}} = v_1(P_2 - P_1)$$

$$w_{\text{pump II,in}} = v_3(P_4 - P_3)$$

REGENERATIVE CYCLE WITH CLOSED FWH



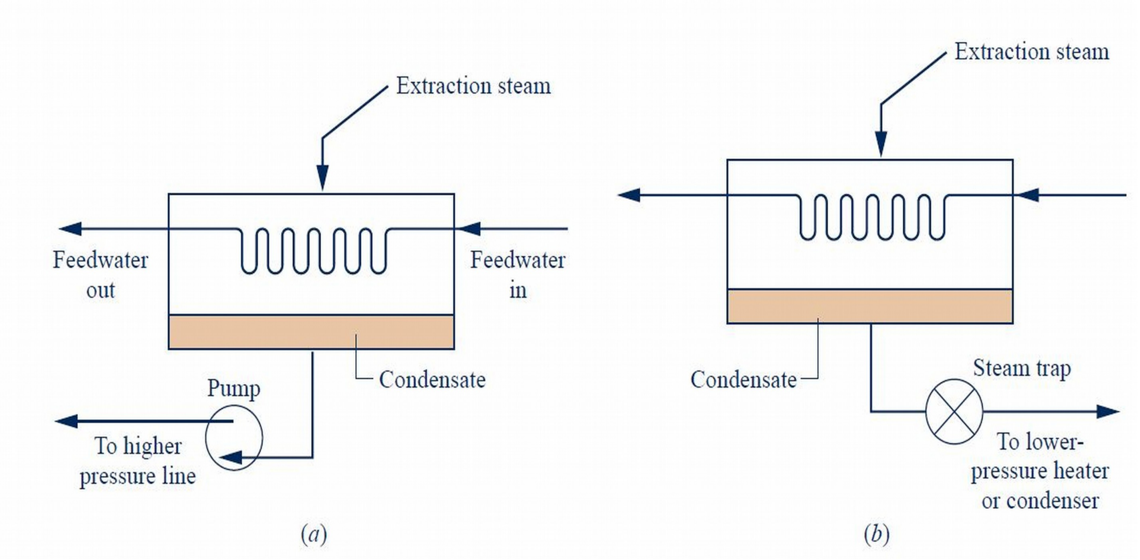
FEED WATER HEATERS:

A feedwater heater is a heat exchanger where heat is transferred from the steam to the feedwater either by mixing the two fluid streams (open feedwater heaters) or without mixing them (closed feedwater heaters). The cycle efficiency increases further as the number of feedwater heaters is increased. Many large plants in operation today use as many as eight feedwater heaters.

COMPARISON OF OPEN AND CLOSED FWH:

Open feedwater heaters are simple and inexpensive and have good heat transfer characteristics. They also bring the feedwater to the saturation state. For each heater, however, a pump is required to handle the feedwater. Power plants with multiple feedwater heaters ordinarily have at least one open feedwater heater operating at a pressure greater than atmospheric pressure so that oxygen and other dissolved gases can be vented from the cycle. This procedure, known as ***deaeration****, is needed to maintain the purity of the working fluid in order to minimize corrosion.*

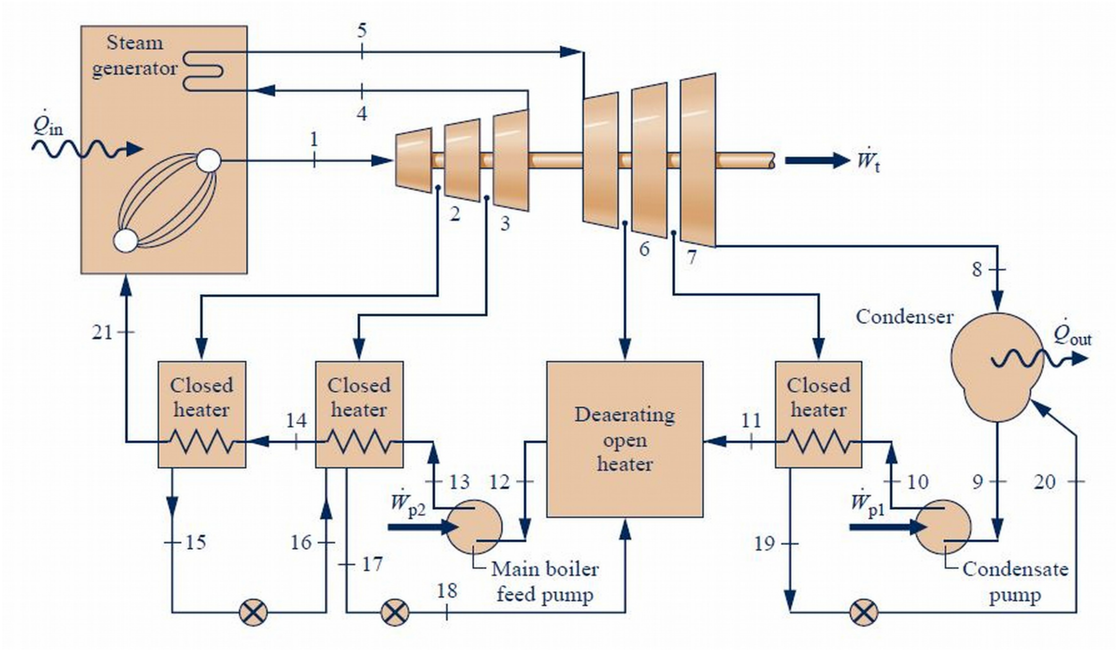
The closed feedwater heaters are more complex because of the internal tubing network, and thus they are more expensive. Heat transfer in closed feedwater heaters is also less effective since the two streams are not allowed to be in direct contact. However, closed feedwater heaters do not require a separate pump for each heater since the extracted steam and the feedwater can be at different pressures.



Closed FWH are shell-and-tube-type recuperators in which the feedwater temperature increases as the extracted steam condenses on the outside of the tubes carrying the feedwater. Since the two streams do not mix, they can be at different pressures. In an ideal closed feedwater heater, the feedwater is heated to the exit temperature of the extracted steam, which ideally leaves the heater as a saturated liquid at the extraction pressure.

The condensed steam is then either pumped to the feedwater line or routed to another heater or to the condenser through a device called a ***trap.*** *A trap allows the liquid to be throttled to a lower pressure region but traps the vapor. The enthalpy of steam remains constant during this throttling process.*

POWER PLANT LAYOUT WITH REHEAT, REGENERATION AND MULTIPLE FWH



COGENERATION

***Cogeneration** is the production of more than one useful form of energy (such as process heat and electric power) from the same energy source. Cogeneration systems are integrated systems that simultaneously yield two valuable products. The most striking feature of the ideal cogeneration plant is the absence of a condenser. No heat is rejected from this plant as waste heat. In other words, all the energy transferred to the steam in the boiler is utilized as either process heat or electric power.*

Cogeneration systems are widely deployed in industrial plants, refineries, chemical, steel making, paper mills, food processing plants, and other facilities requiring process heat, hot water, and electricity for machines, lighting, and other purposes. Cogeneration systems can be based on vapor power plants, gas turbine power plants, reciprocating internal combustion engines, and fuel cells.

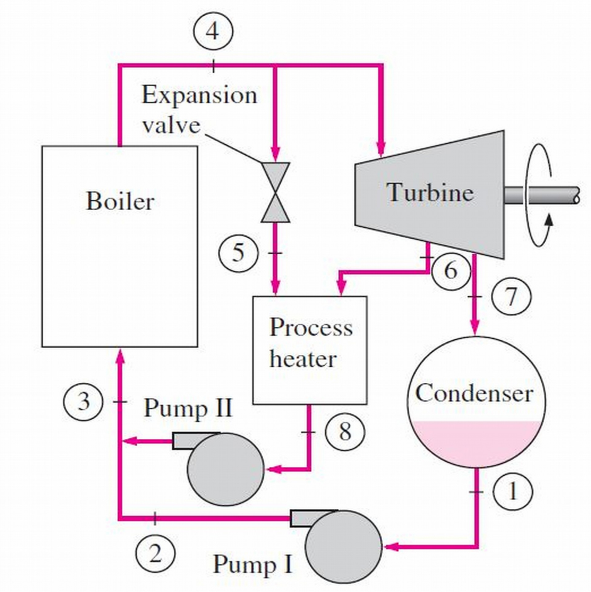
***Utilization factor** for an ideal cogeneration plant is-*

$$\epsilon_u = \frac{\text{Net work output} + \text{Process heat delivered}}{\text{Total heat input}} = \frac{\dot{W}_{\text{net}} + \dot{Q}_p}{\dot{Q}_{\text{in}}}$$

$$\epsilon_u = 1 - \frac{\dot{Q}_{\text{out}}}{\dot{Q}_{\text{in}}}$$

COGENERATION PLANT WITH ADJUSTABLE LOADS

The ideal steam-turbine cogeneration plant is not practical because it cannot adjust to the variations in power and process-heat loads. Under optimum conditions, a cogeneration plant simulates the ideal cogeneration plant. That is, all the steam expands in the turbine to the extraction pressure and continues to the process-heating unit. No steam passes through the PRV (pressure reduction valve /expansion valve) or the condenser; thus, no waste heat is rejected



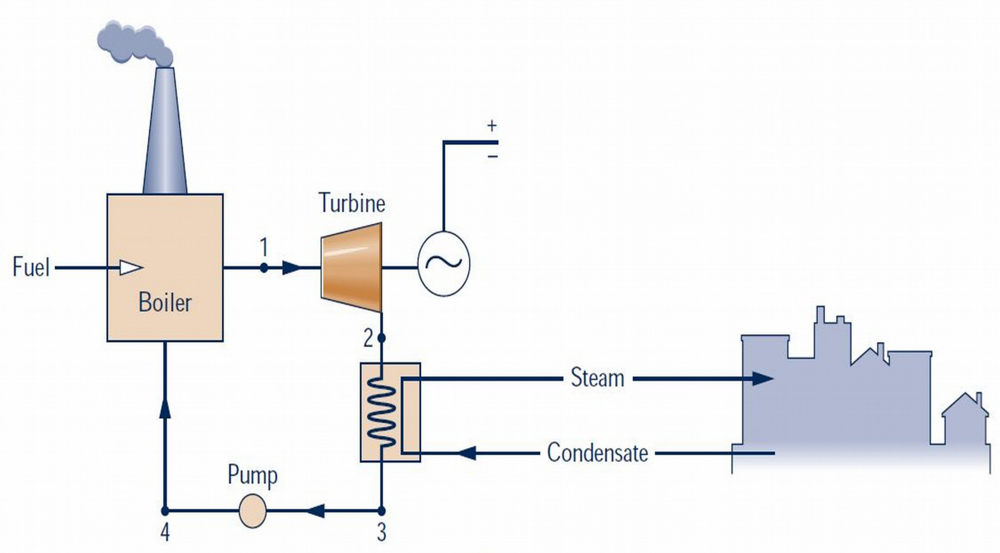
The rates of heat input, heat rejected, and process heat supply as well as the power produced for this cogeneration plant are-

$$\dot{Q}_{\text{in}} = \dot{m}_3(h_4 - h_3)$$

$$\dot{Q}_{\text{out}} = \dot{m}_7(h_7 - h_1)$$

$$\dot{Q}_p = \dot{m}_5 h_5 + \dot{m}_6 h_6 - \dot{m}_8 h_8$$

$$\dot{W}_{\text{turb}} = (\dot{m}_4 - \dot{m}_5)(h_4 - h_6) + \dot{m}_7(h_6 - h_7)$$



(*a*) Back-pressure plant.

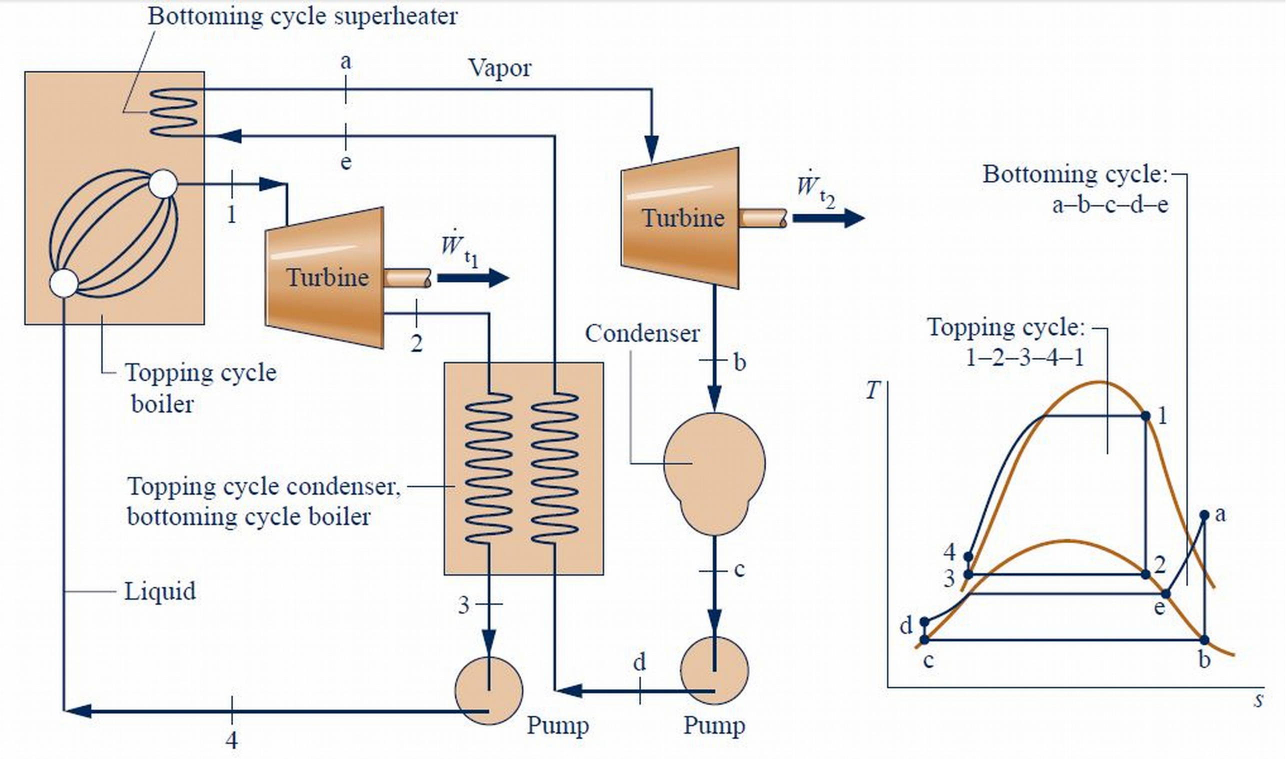
WORKING FLUIDS

Characteristics of working fluid most suitable for vapor power cycles-

1. A high critical temperature and a safe maximum pressure. A critical temperature above the metallurgically allowed maximum temperature (about 620°C) makes it possible to transfer a considerable portion of the heat isothermally at the maximum temperature as the fluid changes phase. This makes the cycle approach the Carnot cycle. Very high pressures at the maximum temperature are undesirable because they create material-strength problems.
2. Low triple-point temperature. A triple-point temperature below the temperature of the cooling medium prevents any solidification problems.
3. A condenser pressure that is not too low. Condensers usually operate below atmospheric pressure. Pressures well below the atmospheric pressure create air-leakage problems. Therefore, a substance whose saturation pressure at the ambient temperature is too low is not a good candidate.
4. A high enthalpy of vaporization so that heat transfer to the working fluid is nearly isothermal and large mass flow rates are not needed.
5. A saturation dome that resembles an inverted U. This eliminates the formation of excessive moisture in the turbine and the need for reheating.
6. Good heat transfer characteristics (high thermal conductivity).
7. Other properties such as being inert, inexpensive, readily available, and nontoxic
Demineralized water is used as the working fluid in the vast majority of vapor power systems because it is plentiful, low cost, nontoxic, chemically stable, and relatively noncorrosive. Water also has a large change in specific enthalpy as it vaporizes at typical steam generator pressures, which tends to limit the mass flow rate for a desired power output. With water, the pumping power is characteristically low, and the techniques of superheat, reheat, and regeneration are effective for improving power plant performance. But water has a low critical temperature (374°C, well below the metallurgical limit) and very high saturation pressures at high temperatures (16.5 MPa at 350°C).

***Organic Rankine cycles** employ organic substances as working fluids, including pentane, mixtures of hydrocarbons, commonly used refrigerants, ammonia, and silicon oil. The organic working fluid is typically selected to meet the requirements of the particular application. For instance, the relatively low boiling point of these substances allows the Rankine cycle to produce power from low-temperature sources, including industrial waste heat, geothermal hot water, and fluids heated by concentrating-solar collectors.*

BINARY VAPOR CYCLES

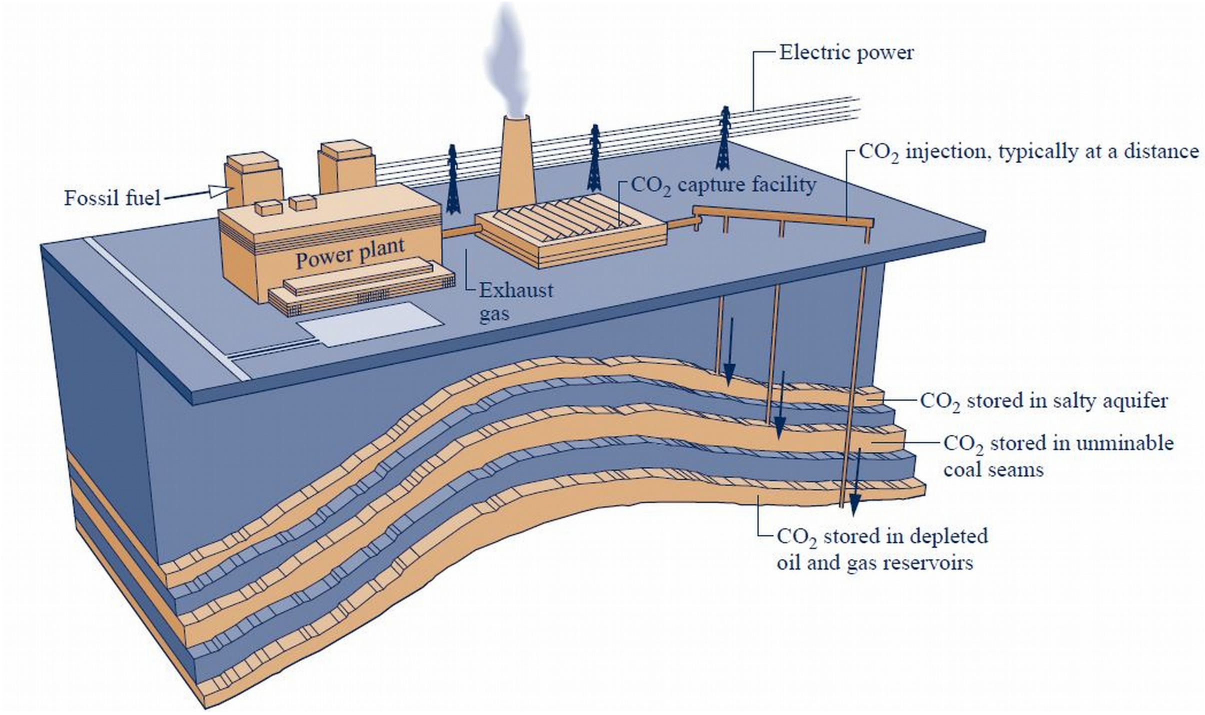


*A **binary vapor cycle** couples two vapor cycles so the energy discharged by heat transfer from one cycle is the input for the other. Different working fluids are used in these cycles, one having advantageous high-temperature characteristics and another with complementary characteristics at the low-temperature. The result is a combined cycle having a high average temperature of heat addition and a low average temperature of heat rejection, and thus a thermal efficiency greater than either cycle has individually. Thermal efficiencies of 50 percent or higher are possible with binary vapor cycles.*

Some working fluids found suitable for the high-temperature cycle are mercury, sodium, potassium, and sodium–potassium mixtures. The critical temperature of mercury is 898°C (well above the current metallurgical limit), and its critical pressure is only about 18 MPa. This makes mercury a very suitable working fluid for the topping cycle. The use of mercury as a working fluid is only limited to the high-temperature cycles. Other disadvantages of mercury are its toxicity and high cost. The mass flow rate of mercury in binary vapor cycles is several times that of water because of its low enthalpy of vaporization.

Binary vapor cycles are not economically attractive because of their high initial cost and the competition offered by the combined gas–steam power plants

CARBON CAPTURE AND STORAGE


Electric power
CO$_2$ injection, typically at a distance
Fossil fuel
CO$_2$ capture facility
Power plant
Exhaust gas
CO$_2$ stored in salty aquifer
CO$_2$ stored in unminable coal seams
CO$_2$ stored in depleted oil and gas reservoirs

Carbon capture and storage is the principal strategy available today for reducing carbon dioxide emissions at the plant level. Captured CO2 is injected into depleted oil and gas reservoirs, unminable coal seams, deep salty aquifers, and other geological structures. Storage in oceans by injecting CO2 to great depths from offshore pumping stations is another method under consideration. Deployment of CO2 capture and storage technology faces major hurdles, including uncertainty over how long injected gas will remain stored and possible collateral environmental impact when so much gas is stored in nature. Another technical challenge is the development of effective means for separating CO2 from voluminous power plant and industrial gas streams.

Use proposed for captured carbon dioxide are-

- ❖ *Enhanced oil recovery—to increase the amount of oil extractable from oil fields. By injecting CO2 at high pressure into an oil-bearing underground layer, difficult to-extract oil is forced to the surface.*
- ❖ *Export of liquefied carbon dioxide by ship from industrialized, oil-importing nations to oil-producing nations.*
- ❖ *To produce algae, a tiny single-cell plant. When supplied with carbon dioxide, algae held in bioreactors absorb the carbon dioxide via photosynthesis, spurring algae growth. Carbon enriched algae can be processed into transportation fuels, providing substitutes for gasoline.*